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Assessing Uncertainty of Pushover Analysis to Geometric Modeling

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***Abstract*— Pushover Analysis a popular tool for seismic performance evaluation of existing and new structures and is nonlinear Static procedure where in monotonically increasing loads are applied to the structure till the structure is unable to resist the further load .During the analysis, whatever the strength of concrete and steel is adopted for analysis of structure may not be the same when real structure is constructed and the pushover analysis results are very sensitive to material model adopted, geometric model adopted, location of plastic hinges and in general to procedure followed by the analyzer. In this paper attempt has been made to assess uncertainty in pushover analysis results by considering user defined hinges and frame modeled as bare frame and frame with slab modeled as rigid diaphragm and results compared with experimental observations. Uncertain parameters considered includes the strength of concrete, strength of steel and cover to the reinforcement which are randomly generated and incorporated into the analysis. The results are then compared with experimental observations.**

***Index Terms*—PushoverAnalysis,uncertainty,geometric modeling, Base shear.**

I. Introduction

Inelastic static analysis, or pushover analysis, has been the preferred method for seismic performance evaluation due to its simplicity. In recent years, the nonlinear pushover analysis method has been viewed as an attractive alternative to the nonlinear time history analysis. This is primarily because of the ability of the nonlinear pushover analysis to provide component and system deformation demands in an approximate manner without the computational and modeling effort of a nonlinear time history analysis. However, an assessment of the uncertainty in the nonlinear pushover analysis methods must be made in order to incorporate this method in the reliability framework of performance-based design [1]. The procedure involves certain approximations and simplifications that some amount of variation is always expected to exist in seismic demand prediction of pushover analysis.

In literature lot of research has been carried out on conventional pushover analysis and after knowing deficiency efforts have been made to improve it. Advantages and disadvantages of Pushover Analysis has been discussed in several publications .Krawinkler and Seneveritna (1998) [2] discussed about Pros and cons of the Push over analysis They presented the precision of this method and identified the cases in which the pushover predictions are misleading. Ashraf Habibullah et al (1998) [3] proposed the procedure for modeling and using SAP2000 performed three dimensional pushover analyses for a building structure. It documents the modeling procedure and defines force-displacement criteria for hinges as documented in ATC-40 and FEMA documents used in pushover analysis. Using SAP2000 software lot of structures have been analyzed for seismic evaluation and if found deficient retrofitting techniques have been suggested. But actual test results to verify the analytically obtained pushover results are rarely available. In this paper attempt is being made to compare analytically obtained results with experimentally obtained results by considering a G+2 storied RCC structure.

II. Description Of The Structure

The structure is a G + 2 stored RCC framed structure . Fig.1 shows the photograph of actual test structure.

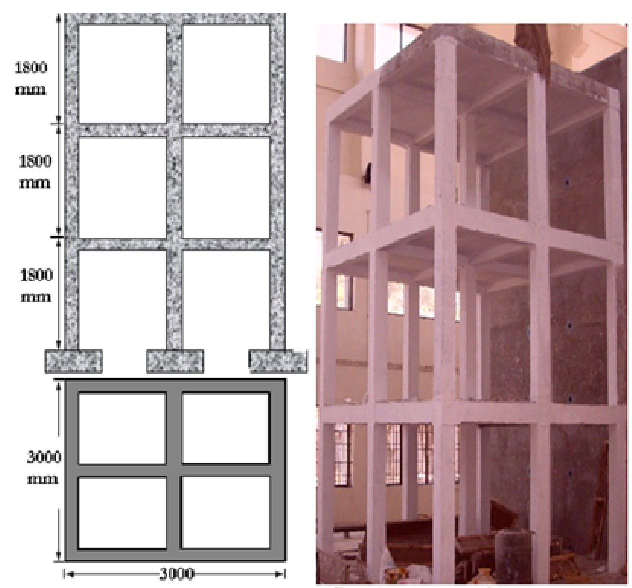

Figure1. Photograph of actual Structure

A. Section Details

Both beam and column sections are 150mm x 200mm in size with 2-12Φ bars at top and bottom in case of beam and 2-16Φ bars at top and bottom in case of columns. The transverse reinforcement for both beams and columns is provided by 2-

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legged 6Φ stirrups/ties @ 150mm c/c. The slab is 50 mm thick. Fig. 2 shows the section properties for the beams and columns.

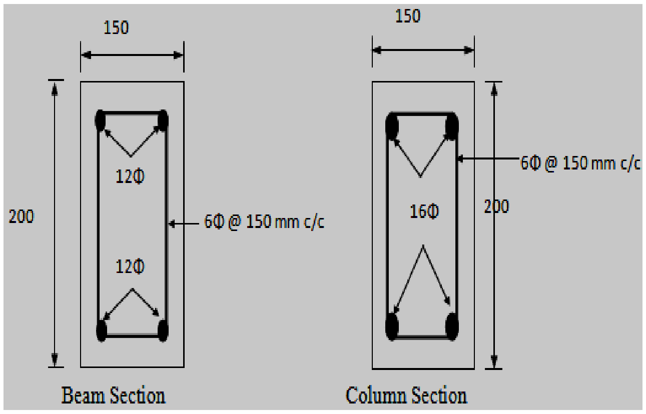

Figure 2 .Section Properties

B. Material Properties

The design material properties for the structure were
Concrete=M20 grade
Steel=Fe415 HYSD bars.
The actual material properties from tests were found as:
Average concrete strength = 35 MPa
Average Reinforcement yield stress = 478 Mpa and
Average Reinforcement ultimate stress = 665 Mpa.

C. Modeling Details

Using the graphical interface of SAP2000 [4] a basic computer model is created and the material properties, Geometric properties defined. The program includes several built-in default hinge properties that are based on average values from ATC-40[5] for concrete members and average values from FEMA-273[6] for steel members. Earlier study on the same model has been carried out by Monica Thapa [7] by considering Kent and Park stress-strain model for confined concrete and British code recommended (CP 110-1972) [8] stress-strain curve for steel. In SAP 2000 there is option of using default hinges or user defined hinges. User defined hinges are more preferred and hence in this paper user defined hinge option is used and for which moment curvature values are obtained by considering IS recommended stress strain model for unconfined concrete shown in Fig.3 and British code recommended (CP 110-1972) stress-strain curve for steel as shown in Fig.4.

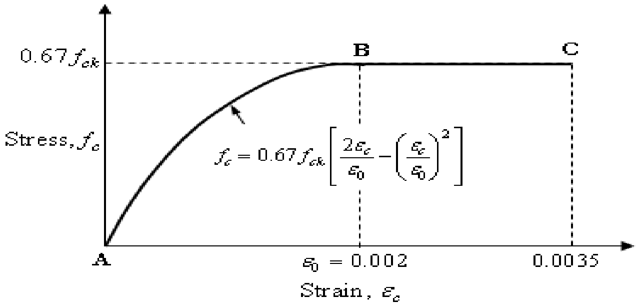

Figure 3. IS recommended stress strain model for unconfined concrete

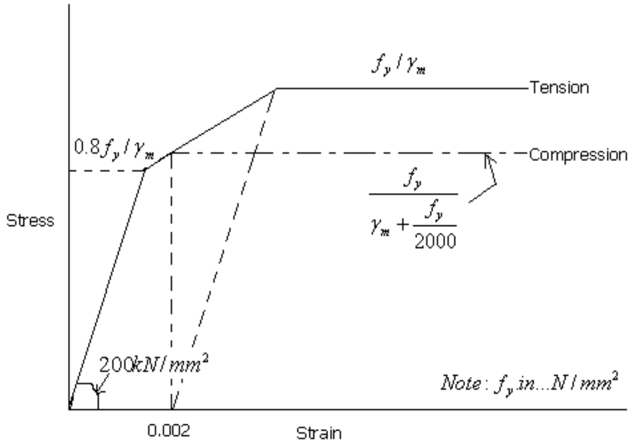

Figure 4. British code recommended (CP 110-1972) stress-strain curve for steel

Moment curvature data is generated using Equilibrium and compatibility equations and the generated values are shown in Table I and Table II for columns and beams respectively. Actual material properties were used in performing the analysis. The moment values are in kN-m.

TABLE I. MOMENT CURVATURE VALUES FOR COLUMNS

Points	A	B	C	D	E
	Origin	Yielding	Ultimate	Strain hardening	Strain hardening
fy=478N/mm2	M=0	M=21.55	M=23.34	M=25.12	M=26.94
fck=35N/mm2	Φ=0	Φ=0.0134	Φ=0.088	Φ=0.099	Φ=0.111

TABLE II. MOMENT CURVATURE VALUES FOR BEAMS

Points	A	B	C	D	E
	Origin	Yielding	Ultimate	Strain hardening	Strain hardening
fy=478N/mm2	M=0	M=12.76	M=14.58	M=16.40	M=18.23
fck=35 N/mm2	Φ=0	Φ=0.011	Φ=0.078	Φ=0.090	Φ=0.105

To incorporate elemental nonlinearity M3 plastic hinges (user-defined) was assigned to beam and columns at both ends of the beams and columns. The pushover load cases are then defined. The first pushover load case is used to apply gravity load and then subsequent lateral pushover load cases are specified to start from the final conditions of the gravity pushover. lateral load distributed across the height of the building is found out based on the formula specified in

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FEMA 356 [9], given by equation(1) and then in-cooperated in the model.

$$F_x = \frac{W_x h_x^k}{\sum_{i=1}^{N} W_i h_i^k} V \qquad (1)$$

$$C_{vx} = \frac{W_x h_x^k}{\sum_{i=1}^{N} W_i h_i^k}$$

Where, Fx is the applied lateral force at level ' x ', W is the storey weight, h is the story height, V is the design base shear and N is the number of stories. Cvx is the coefficient that represents the lateral load multiplication factor to be applied at floor level ' x '.The load pattern for tests was kept as parabolic with the load value at a storey increasing in proportion to the square of the height of the floor from foundation level.

The pushover load case PUSH for the pushover analysis was applied laterally to the model created, as a point load at each storey in the ratio of 9:4:1 for roof: 2nd floor: 1st floor as calculated using above equations. Displacement controlled Nonlinear static pushover analysis is defined for the present study.

III. Experimentally Obtained Pushover Analysis Results

The reinforced concrete frame model was tested at SERC (Structural Engineering Research Centre) Chennai (Fig. 1) with section details as shown in (Fig .2). Load has been applied monotonically in the ratio of 9:4:1 for roof: 2nd floor: 1st floor by pushing it with the help of hydraulic jacks. Then load versus displacement curve was obtained (i.e. experimental pushover curve) and the maximum base shear observed was 286.5 kN and the corresponding displacement was found to be 110mm i.e. 0.11m.

IV. Analysis

Initial study is carried out by considering the actual material properties of the test results and modeling of the frame is done in SAP2000.Userdefined hinge properties are incorporated by inputting moment curvature data generated as shown in Table I and Table II. Two frame models are considered for carrying out this study.viz Frame modeled as bare frame and frame with slab modeled as rigid diaphragm. Slabs were modeled using the four node quadrilateral shell elements, which is an area element used to model slabs/plates in planar and three dimensional structures. SAP 2000 offers features such that slab can be modeled as a shell element as well as a rigid diaphragm. In present study slab is modeled as rigid diaphragm. The results of pushover Analysis carried out is shown in Fig.5 and Fig.6 respectively.

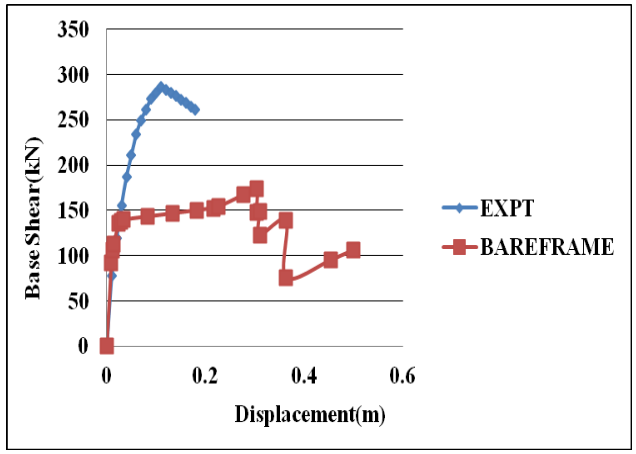

Figure 5. Comparison of experimental pushover results with analytical (Bareframe)

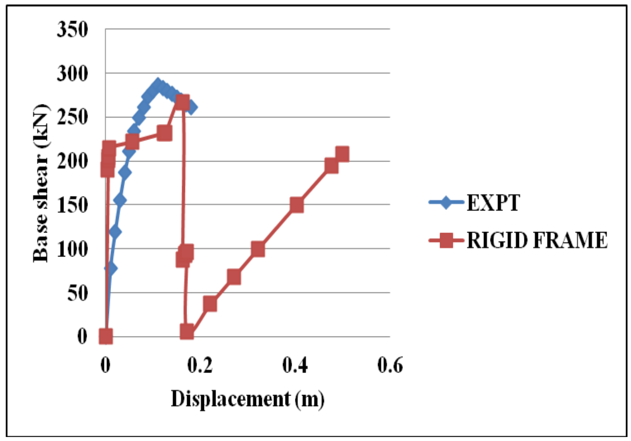

Figure 6. Comparison of experimental pushover results with analytical (Rigid frame)

For the frame modeled as bare frame the corresponding P (Base Shear) and Δ (Displacement)were found to be 173.8kN and 0.31m respectively .For frame with slab modeled as rigid diaphragm the corresponding P (Base Shear) and Δ (Displacement)were found to be 267kN and 0.16m respectively. Thus from above analysis it is clear that there is some variation in Base shear and Displacement values when compared with experimental values for the various geometric models considered. Hence the results are highly sensitive to geometric modeling.

Since average values of strength of concrete , strength of steel and cover to reinforcement was adopted in above analysis, in actual structure constructed there is a possibility that there could be variation in grade of concrete, grade of steel and cover to the reinforcement, on account of which the experimental results may differ from analytical results. To assess this uncertainty, further progress of the work is carried out by adopting the same geometric models and considering uncertain parameters as grade of steel, grade of concrete and cover to the reinforcement. Considering lower and upper limit as 15% decrease and 15% increase in reference grade of steel ($fy=478N/mm^2$), reference grade of concrete ($fck=35N/mm^2$) and Cover(20mm), random numbers were generated and in - cooperated in analysis. Excel program was done to get newly generated moment curvature data. For each combination of

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above mentioned uncertain parameters, the new moment curvature data is generated and incoperated in SAP2000 as user defined hinge properties in the model ..

About 200 iterations for each model is carried out by using model alive and data base interactive editing in SAP2000.User defined hinge properties and default hinge length is adopted in performing the analysis. The results of pushover analysis for rigid frame are shown in Table III.

TABLE III. P AND Δ VALUES FOR RANDOMLY GENERATED VALUES OF FCK, FY AND COVER(RIGID FRAME)

Sr.No	fck	fy	Cover	P	Δ
1	39.31	507.6	24.05	287.16	0.176
2	39.56	431.73	19.38	268.4	0.169
3	32.34	501.57	26.89	262.9	0.21
4	38.20	471.22	20.75	271.8	0.16
5	29.67	500.45	17.26	274.74	0.18
6	31.82	431.9	11	261.18	0.2
7	37.11	410.48	24.13	245.3	0.19
8	33.33	443.18	26.03	246.80	0.2
9	34.36	494.5	12.97	292.23	0.187
10	32.57	496.69	26.28	266.59	0.21
11	39.50	466.06	14.31	295.27	0.18
12	40.20	408.73	17.7	258.14	0.176
13	37.80	499.25	11.67	303.5	0.18
14	39.23	486.64	29.87	258	0.19
15	37.60	416.49	11.26	272.6	0.17
16	29.88	492.99	18.96	274.26	0.21
17	37.01	486.46	14.07	293.77	0.185
18	37.95	476.43	11.73	287	0.17
19	35.53	446.88	13.87	268.9	0.17
20	33.54	437.96	13.01	274.4	0.18
21	29.98	473.7	23.54	253.26	0.2
22	29.18	428.23	12.82	256.68	0.18
23	34.38	484.72	18.73	282.2	0.19
24	34.8	409.04	24.86	228.91	0.18
25	33.04	455.57	10.68	272.52	0.17
26	35.43	449.02	13.77	267.66	0.17
27	38.22	495.48	20.13	289.09	0.19
28	36.52	523.3	22.76	251.4	0.15
29	36.88	517.52	16.43	303.15	0.19
30	32.07	415.72	10.50	251.89	0.16
31	30.74	427.84	28.22	195.89	0.15
32	36.82	523.56	25.99	280.84	0.2
33	37.35	464.6	27.76	252.22	0.19
34	39.12	459	22.62	276.04	0.19
35	30.96	538.28	22.16	287	0.22
36	32.18	521.33	28.77	270.68	0.23
37	29.36	457.49	12.72	270.5	0.19
38	31.25	442.34	14.52	252.46	0.17
39	30.74	503.25	10.59	298.02	0.2
40	31.62	468.89	16.1	266.17	0.18
41	29.07	507.92	12.96	276.65	0.19
42	33.45	439.58	18.54	262.73	0.19
43	33.45	439.58	18.54	262.73	0.19
44	34.97	528.47	17.17	301.94	0.2
45	31.05	419.81	17.32	248.43	0.18
46	29.83	461.88	20.62	258.97	0.2
47	32.65	444.86	13.87	264.64	0.18
48	39.15	477.03	20.49	278.4	0.186
49	30.8	438.19	15.49	264.54	0.19
50	39.89	450.65	20.61	265.82	0.18
51	32.66	466.41	24.17	259.5	0.2
52	39.81	497.6	29.97	278.98	0.21
53	36.51	474.94	20.73	277.55	0.196
54	37.58	418.46	20.33	254.8	0.180
55	33.48	421.19	13.13	257.8	0.17
56	30.50	458.65	14.3	261.3	0.18
57	37.73	524.69	28.71	281.6	0.21
58	33.07	468.89	21.77	267.38	0.2
59	40.15	528.64	10.04	321.27	0.17
60	29.51	438.82	24.14	237.23	0.20
61	36.5	481.75	18.52	281.17	0.19
62	35.03	512.81	10.23	301.05	0.17
63	36.02	418.25	24.62	236.37	0.18
64	36.04	493.10	16.69	279.08	0.18
65	31.47	498.79	28.69	252.56	0.21
66	29.91	484.28	28.41	272.87	0.25
67	35.74	506.04	18.04	291.58	0.19
68	39.59	450.10	11.27	282.27	0.169
69	34.94	408.5	29.85	220.91	0.187
70	35.49	495.42	24.93	276.73	0.21
71	35.73	429.73	11.50	277.2	0.18
72	30.72	546.36	21.60	285.03	0.22
73	34.07	506.56	19.59	274.75	0.189
74	28.81	484.35	27.28	249.23	0.22
75	33.91	478.39	29.85	256.42	0.218
76	36.82	439.09	29.94	247.62	0.20
77	33.73	436.63	15.49	253.17	0.17
78	39.84	434.30	27.33	254.02	0.195
79	36.36	526.95	18.57	292.66	0.19
80	37.22	470.01	19.89	266.29	0.17
81	33.11	431.83	17.13	268.74	0.19
82	31.63	453.55	20.44	260.08	0.20
83	33.83	418.11	15.01	257.5	0.18
84	33.76	463.58	12.95	237.45	0.14
85	32.64	432.38	13.50	266.88	0.18
86	31.09	427.09	10.28	260.7	0.17
87	39.74	463.61	22.24	280.65	0.19
88	39.78	450.48	19.13	268.04	0.17
89	34.66	427.65	22.76	248.5	0.19
90	33.72	539.99	27.71	283.66	0.23
91	31.31	507.05	17.90	271.7	0.19
92	33.48	519.76	29.65	264.13	0.21
93	32.34	479.53	22.93	257.59	0.19
94	30.5	477.16	19.21	265.71	0.20
95	34.04	441.72	14.64	274.81	0.19
96	36.95	429.81	23.68	242.91	0.179
97	36.99	534.49	12.11	310.62	0.18
98	32.12	513.61	29.04	255.4	0.21
99	36.87	435.31	28.78	250.70	0.206
100	31.59	451.72	15.10	270.38	0.19
101	34.86	498.46	13.11	296.58	0.18
102	37.20	546.66	16.96	319.10	0.2
103	38.67	458.82	26.91	263.67	0.2
104	39.61	424.89	21.64	225.57	0.14
105	33.01	475.36	12.48	284.5	0.18
106	35.89	517.67	23.78	279.11	0.2
107	28.79	486.78	10.60	281.22	0.19
108	38.95	450.13	15.71	269.12	0.17
109	39.79	464	25.43	273.33	0.2
110	32.16	428.5	28.16	235.87	0.2
111	39.48	536.41	18.3	317.4	0.2
112	39.46	486.43	29.23	268.46	0.22
113	29.83	544.05	28.96	261.89	0.23
114	37.12	510.4	14.28	310	0.19
115	29.76	442.79	22.18	242.36	0.19
116	37.7	418.24	29.31	238.39	0.19
117	35.70	407.57	10.10	261.97	0.16
118	37.88	423.46	23.19	250.7	0.18
119	39.52	517.54	19.98	296.3	0.19
120	30	480.31	22.14	255.38	0.2
121	34.17	455.85	19.96	263.6	0.19
122	30.75	464.6	14.82	261.8	0.18
123	32.99	409.6	27.41	229.5	0.196
124	31.42	542.61	20.18	295	0.22
125	35.75	463.87	26.85	255.2	0.21

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126	30.70	467.86	26.67	253.8	0.22
127	28.90	430.4	21.2	238.38	0.197
128	33.15	540.41	26.68	281	0.22
129	31.05	524.67	13.33	292.2	0.196
130	39.3	465.5	27.86	264.5	0.2
131	29.73	456.63	29.74	213.19	0.19
132	39.43	520.3	25.45	283.36	0.19
133	37.42	459.84	26.95	255.34	0.19
134	34.77	517.66	24.19	286.48	0.21
135	33.74	498.60	24.35	263.54	0.19
136	37.55	533.26	11.97	315.80	0.18
137	29.58	437.31	12.37	227.82	0.14
138	37.19	533.27	10.54	315.89	0.18
139	35.43	483.16	20.28	269.2	0.18
140	29.71	484.48	17.32	261.61	0.19
141	32.04	439.00	18.17	252.47	0.18
142	31.21	430.71	24.23	235.84	0.193
143	36.66	504.49	22.28	290.44	0.20
144	38.69	459.95	23.51	271.09	0.19
145	40.20	472.71	21.95	243.78	0.15
146	34.01	424.67	15.52	257.05	0.179
147	32.73	503.21	10.25	300.18	0.19
148	38.84	515.32	29.19	271.72	0.2
149	31.36	487.58	23.74	262.8	0.21
150	32.73	423.66	19.77	239.52	0.177
151	37.98	492.96	14.42	299.77	0.187
152	33.76	478.20	10.29	295.13	0.188
153	28.99	474.82	1094.	268.26	0.182
154	39.14	502.31	25	247.39	0.16
155	38.25	481.4	21.59	288.06	0.20
156	37.48	548.64	16.37	322.5	0.2
157	36.31	513.17	22.32	286.1	0.2
158	31.03	492.	19.15	268.5	0.199
159	30.40	462.61	15.41	257.9	0.182
160	35.84	457.53	23.83	268.2	0.20
161	31.50	427.13	16.68	252.31	0.18
162	36.80	547.62	19.55	309.6	0.20
163	32.77	516.44	15.56	287.8	0.19
164	39.84	539.85	17.05	322.96	0.20
165	33.29	531.70	25.09	286.81	0.22
166	35.22	537.73	29.74	275.52	0.22
167	30.95	507.38	29.98	259.44	0.23
168	32.48	538.46	25.07	279	0.219
169	29.10	448.87	14.95	264.83	0.2
170	31.89	527.12	20.07	285.83	0.21
171	39.97	547.5	28.08	296.76	0.21
172	35.45	519.10	26.73	269.38	0.20
173	37.55	426.4	10.77	271.75	0.17
174	37.81	408.02	14.72	268.90	0.18
175	39.05	435.19	14.54	274.05	0.176
176	35.80	547.34	22.73	296.25	0.206
177	40.24	494.43	19.60	285.30	0.182
178	38.74	416.82	13.94	252.82	0.18
179	34.24	535.79	10.37	309.06	0.185
180	37.57	472.74	14.42	279.82	0.173
181	31.16	504.66	21.11	280.01	0.22
182	36.10	474.06	21.16	271.6	0.19
183	34.37	540.33	26.75	275.01	0.20
184	37.09	518.68	22.70	255.12	0.16
185	38.45	474.65	23.31	267.54	0.1876
186	30.33	430.81	16.27	243.28	0.177
187	35.75	414.54	20.07	243.29	0.176
188	31.16	435.58	29.10	226.11	0.197
189	39.89	475.99	19.84	285.19	0.189
190	28.89	434.17	29.75	222.71	0.20
191	31.07	521.36	27.04	264.84	0.22
192	39.43	520.3	25.45	283.36	0.19
193	37.42	459.84	26.95	255.34	0.19
194	34.77	517.66	24.19	286.48	0.21
195	33.74	498.60	24.35	263.54	0.19
196	37.55	533.26	11.97	315.80	0.18
197	29.58	437.31	12.37	227.82	0.14
198	37.19	533.27	10.54	315.89	0.18
199	35.43	483.16	20.28	269.2	0.18
200	29.71	484.48	17.32	261.61	0.19

The statistical analysis for the above generated data is carried out in Minitab(version 16).Hypothetical testing of generated data is carried out to assess uncertainty by considering target value of base shear and displacement as the Experimental values viz, P=286.5kN and Δ=0.11m.

The results of one sample t-test carried out is shown in Table IV and Table V.

TABLE IV. HYPOTHETICAL TEST RESULTS FOR BASE SHEAR

Frame type	Mean (P) kN	Stdev(P)	95% Confidence Interval
Bare Frame	176.1	14.45	(174.05,178.08)
Rigid frame	269.6	22.14	(266.54, 272.72)

TABLE V. HYPOTHETICAL TEST RESULTS FOR DISPLACEMENT

Frame type	Mean Δ(m)	Stdev(Δ)	95% Confidence Interval
Bare Frame	0.352	0.019	(0.35005, 0.3554)
Rigid frame	0.19	0.017	(0.18758, 0.1925)

V. RESULTS AND DISCUSSIONS

Considering material properties from test results and adopting IS recommended stress strain model for unconfined concrete, British code recommended (CP 110-1972) stress-strain curve for steel, Analysis was carried out in SAP2000.Userdefined hinge properties were in-cooperated and hinges are applied at ends of beams and columns. Two frame models were considered for carrying this study.viz Frame modeled as bare frame and frame with slab modeled as rigid diaphragm frame . It has been found that in all the models considered there is difference in values of base shear and displacement when compared to experimental values. Bare frame gives lowest values for base shear and highest values for displacement .Thus we see that the results of pushover analysis are sensitive to geometric models adopted.

To further investigate the variation of experimental results when compared to analytical, Monte Carlo simulation technique was adopted by generating random uncertain parameters viz. fck, fy and cover for all the frame models by carrying out 200 iterations using database interactive editing in SAP2000.

Hypothetical Testing of data generation is done in Minitab for base shear by considering Null hypothesis as

$H_o: P = 286.5$ and alternative hypothesis as

$H_a: P \neq 286.5$

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and for displacement by considering Null hypothesis as

Ho: $\Delta = 0.11$ and alternative hypothesis as

Ha: $\Delta \neq 0.11$

The results of t-test carried out for base shear shows that the mean of the sample differs from 286.5 for the models considered and 95 % confident interval lies between (174.05-178.08) and (266.54- 272.72) for bare frame and rigid frame model respectively.

The results of t-test carried out for Displacement shows that the mean of the sample differs from 0.11m for the two models and 95 %confident interval lies between (0.35005-0.3554) and (0.18758-0.1925) for bare frame and rigid model respectively.

VI. Conclusion

It has been observed that there is variation between analytically obtained pushover results when compared to experimental values for the geometric models considered. The large variation between the observed test results and the predicted behavior from analytical models needs consideration and refinement .It can be concluded that the variation is because the pushover results are very sensitive to geometric model and material model adopted Further study needs to be carried out by considering other material models ,random hinge location and random hinge lengths calculated from various formulations available in literature and the results compared with experimental observations .Also frame with slab modeled as shell can be considered as geometric model and results compared with bare frame and rigid frame model.

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